

A compiled catalog of rotation measures of radio point sources

Jun Xu^{1,2} and Jin-Lin Han¹

¹ National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China;
hjl@nao.cas.cn

² University of Chinese Academy of Sciences, Beijing 100049, China

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Abstract We compiled a catalog of Faraday rotation measures (RMs) for 4553 extragalactic radio point sources published in literature. These RMs were derived from multi-frequency polarization observations. The RM data are compared to those in the NRAO VLA Sky Survey (NVSS) RM catalog. We reveal a systematic uncertainty of about $10.0 \pm 1.5 \text{ rad m}^{-2}$ in the NVSS RM catalog. The Galactic foreground RM is calculated through a weighted averaging method by using the compiled RM catalog together with the NVSS RM catalog, with careful consideration of uncertainties in the RM data. The data from the catalog and the interface for the Galactic foreground RM calculations are publicly available on the webpage: <http://zmtt.bao.ac.cn/RM/>.

Key words: catalogs — polarization — radio continuum: ISM — ISM: magnetic fields

1 INTRODUCTION

When a polarized signal propagates through a magnetized medium, the plane of polarization is rotated, and this rotation depends on frequency. This is the Faraday effect discovered by M. Faraday in 1844. The polarization angle ψ is thus equal to

$$\psi = \psi_0 + \text{RM} \cdot \lambda^2, \quad (1)$$

where ψ_0 is the intrinsic polarization angle, and the rotation of the polarization angle $\Delta\psi = \psi - \psi_0$ is proportional to the wavelength squared, λ^2 , with a rate RM in units of rad m^{-2} . This is the rotation measure (RM), which is an integrated quantity of the product of the free electron density n_e and magnetic field strength B along the line of sight from the source to us, and is expressed by

$$\text{RM} = 0.81 \int_{\text{source}}^{\text{us}} n_e B \cdot dl. \quad (2)$$

The electron density n_e is in cm^{-3} , the magnetic field is a vector B in units of μG , and dl is the unit vector along the light path towards us in units of pc. Only the component of the magnetic field along the line of sight determines the amount of Faraday rotation.

If there is no $n\pi$ ambiguity for the polarization angles, the RM value of a polarized radio point source can be determined by polarization observations at two frequencies, through

$$\text{RM} = (\psi_1 - \psi_2) / (\lambda_1^2 - \lambda_2^2). \quad (3)$$

Here ψ_1 and ψ_2 are the polarization angles at the wavelengths λ_1 and λ_2 . Because of the $n\pi$ ambiguity in ψ values, in practice polarization angles at at least three frequencies are needed to determine RM. When multi-frequency polarization observations are available from a radio source, the slope of a linear fit to polarization angles against wavelength squared is the RM, if the polarization angles have been properly unwrapped to correct for the $n\pi$ ambiguity.

The RMs of many radio sources have been determined well using multi-frequency polarization observations. In the early days, polarization observations were carried out for strong radio sources with single-dish radio telescopes, and measurements of polarization angles at several frequencies were used to estimate RMs (e.g. sources in Simard-Normandin et al. 1981; Broten et al. 1988). Later, synthesis radio telescopes were used for polarization observations with excellent resolutions, so that RMs of different emission components of radio sources could be measured separately (e.g. Minter & Spangler 1996). Recently, wideband observations have made it possible to determine RMs from a set of measured ψ values of many channels in a single frequency band (e.g. Brown et al. 2003), or directly from the Stokes Q and U values of the channel maps using the technique of RM synthesis (Brentjens & de Bruyn 2005).

Observations for RMs have great scientific merits. RMs of radio sources in small regions on the sky have been used to probe the magnetic fields in galaxy clusters (Hennessy et al. 1989; Clarke et al. 2001; Johnston-Hollitt & Ekers 2004; Govoni et al. 2010; Bonafede et al. 2010), in nearby galaxies (Han et al. 1998; Gaensler et al. 2005; Mao et al. 2008, 2012; Gießübel et al. 2013), in stellar bubbles (Savage et al. 2013) or HII regions (Harvey-Smith et al. 2011; Rodríguez et al. 2012) and even supernova remnants (SNRs: Kim 1988; Simonetti 1992; Sun et al. 2011), and high velocity clouds (McClure-Griffiths et al. 2010) in our Milky Way. RMs of radio sources behind the Galactic disk revealed the magnetic structure in the disk (Simard-Normandin & Kronberg 1980; Sofue & Fujimoto 1983; Brown et al. 2007; Van Eck et al. 2011). The RM distribution over the whole sky has been used for delineating magnetic fields in the Galactic halo (Han et al. 1997, 1999) and for deriving the Galactic foreground RM (Oppermann et al. 2012).

Early RM catalogs of galaxies or quasars were compiled by, for example, Eichendorf & Reinhardt (1979) and Tabara & Inoue (1980). The most often used are the RM catalogs for 555 objects by Simard-Normandin et al. (1981) and 674 objects by Broten et al. (1988). Over the last ten years, RMs of a large number of extragalactic radio sources (EGRs) have been derived in many surveys, for example, the Canadian Galactic Plane Survey (Brown et al. 2003) and the Southern Galactic Plane Survey (Brown et al. 2007). Observations of specific regions also increased the total number of RM data, such as those for the Large Magellanic Cloud (Mao et al. 2012), the Small Magellanic Cloud (Mao et al. 2008) and the Galactic poles (Mao et al. 2010). These RMs are in general well determined, because the polarization angles of many frequency channels have been used to derive the RM values.

We have extensively searched literature published in the last two decades for RM data. In Section 2, we publish our compilation of RM data for 4553 point sources, which should be valuable for many research projects, as mentioned above. Archival surveys and databases are checked for possible associations of radio sources with known objects, sometimes even with known redshifts. Taylor et al. (2009) have reprocessed the 2-channel polarization data from the NRAO VLA Sky Survey (NVSS, Condon et al. 1998), and obtained RMs for 37 543 sources. In Section 3 we will also compare the RM values that we compiled with those in the NVSS RM catalog of Taylor et al. (2009). We will show the distribution of RM uncertainties, and derive the Galactic foreground RMs in Section 4 by using the weighted averages of RM data. Discounting such a foreground RM is important, for example, to calculate the intrinsic RMs of radio sources (e.g. Leahy 1987; Athreya et al. 1998; Broderick et al. 2007; Schnitzler 2010) and to understand the magnetic fields in galaxy clusters (e.g. Clarke et al. 2001; Bonafede et al. 2010, 2013).

Table 1 A Compiled Catalog of Faraday Rotation Measures for Point Radio Sources

No.	RA(J2000) hh mm ss.ss	Dec(J2000) dd mm ss.ss	Note	GLong. ($^{\circ}$)	GLat. ($^{\circ}$)	RM rad m $^{-2}$	σ_{RM} rad m $^{-2}$	Gd G+	Ref1.	Telescope	Freq1 - Freq2 (GHz)	Nfre	Reso ($''$)	OBJe	z.Obje	Ref2.	Remark
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
00001	00 00 00.1	+67 08 00	O	117.953	4.760	-411	29	C	btj03	DRAO/ST	1.402 - 1.437	4	60				
00002	00 00 31.6	+66 52 43	O	117.953	4.500	-88	16	C	btj03	DRAO/ST	1.402 - 1.437	4	60				
00003	00 00 38.4	+43 57 48	O	113.36	-17.97	-70	8	B	mmg+12a	VLA/D.Dnc	1.365 - 1.486	14	60				
00004	00 01 00.91	-25 04 51.90	O	40.359	-78.502	16	5	B	mgH+10	ATCA	1.384 - 2.368	64	30				
00005	00 01 10.60	-33 29 28.90	O	359.465	-77.438	8	3	A	mgH+10	ATCA	1.384 - 2.368	64	30				
00006	00 01 28.8	+41 04 24	O	112.89	-20.82	-74	14	C	mmg+12a	VLA/D.Dnc	1.365 - 1.486	14	60				
00007	00 01 53.37	-30 25 08.50	O	13.143	-78.662	4	2	A	mgH+10	ATCA	1.384 - 2.368	64	30	GAL	1.3025	NED	
00008	00 01 55.2	+36 22 48	O	111.92	-25.44	-104	13	C	mmg+12a	VLA/D.Dnc	1.365 - 1.486	14	60				
00009	00 01 55.63	-21 49 59.80	O	55.438	-77.562	4	3	A	mgH+10	ATCA	1.384 - 2.368	64	30				
00010	00 02 11.96	-21 53 09.20	O	55.357	-77.642	6	1	A	mgH+10	ATCA	1.384 - 2.368	64	30	GAL			
00011	00 02 31.33	-34 26 14.1	O	355.082	-77.218	-6	2	A	bbh+07	ATCA	1.384 - 2.368	5	15.8	RAG			J000231-342614N*
00012	00 02 31.33	-34 26 14.1	O	355.082	-77.218	3	6	B	bbh+07	ATCA	1.384 - 2.368	5	15.8	RAG			J000231-342614S*
00013	00 02 45.32	-30 28 37.50	O	12.622	-78.829	31	2	A	mgH+10	ATCA	1.384 - 2.368	64	30				
00014	00 02 55.61	-26 54 47.00	O	31.306	-79.198	8	4	B	mgH+10	ATCA	1.384 - 2.368	64	30	GAL	0.0666	NED	
00015	00 03 01.37	-31 18 10.10	O	8.483	-78.650	11	6	B	mgH+10	ATCA	1.384 - 2.368	64	30				
00016	00 03 04.21	-33 12 05.30	O	359.832	-77.922	2	3	A	mgH+10	ATCA	1.384 - 2.368	64	30				
00017	00 03 19.2	+43 34 36	O	113.77	-18.44	-51	8	B	mmg+12a	VLA/D.Dnc	1.365 - 1.486	14	60				
00018	00 03 25.58	-27 26 35.80	O	28.487	-79.332	24	5	B	mgH+10	ATCA	1.384 - 2.368	64	30				
00019	00 03 34.8	+62 47 43	O	117.493	0.430	-355	14	C	btj03	DRAO/ST	1.402 - 1.437	4	60				
00020	00 03 41.05	-31 04 00.30	O	9.408	-78.857	76	30	C	mgH+10	ATCA	1.384 - 2.368	64	30				
.....																	
00031	00 04 20.42	-28 40 11.50	O	21.772	-79.485	49	5	B	mgH+10	ATCA	1.384 - 2.368	64	30				
00032	00 04 22.38	-23 07 33.20	O	50.947	-78.627	16	24	C	mgH+10	ATCA	1.384 - 2.368	64	30				
00033	00 04 24.6	+67 30 22	O	118.443	5.045	-134	40	D	btj03	DRAO/ST	1.402 - 1.437	4	60				
00034	00 04 28.35	-30 57 34.40	O	9.674	-79.051	16	6	B	mgH+10	ATCA	1.384 - 2.368	64	30				
00035	00 04 28.8	+56 14 12	O	116.40	-6.04	-56	7	B	mmg+12a	VLA/D.Dnc	1.365 - 1.486	14	60				
00036	00 04 50.2	+12 48 40	O	105.6	-48.5	-17	2	A	skb81	various	? - ?	? ?	GAL				0002+12 P
00036.1	00 04 50.2	+12 48 40	O	105.6	-48.5	-17	2	A	bmv88	various	? - ?	? ?	GAL			bmv88	0002+1232 P
00037	00 04 54.9	+62 29 18	O	117.588	0.100	-323	33	D	btj03	DRAO/ST	1.402 - 1.437	4	60				
00038	00 04 55.2	+44 27 48	O	114.25	-17.63	-59	12	C	mmg+12a	VLA/D.Dnc	1.365 - 1.486	14	60				
00039	00 05 07.2	+40 57 60	O	113.58	-21.08	-72	23	C	mmg+12a	VLA/D.Dnc	1.365 - 1.486	14	60				
00040	00 05 16.8	+55 17 12	O	116.34	-6.99	-53	14	C	mmg+12a	VLA/D.Dnc	1.365 - 1.486	14	60				
.....																	

Notes: Col. (1): Source number. Additional RM values in literature are indicated with “_l” and “_2” or “_n” for reference; Col. (2) and (3): Right ascension and declination (J2000) of a source; Col. (4): Note on source position: ‘O’ stands for the *original* position from literature of RM measurements, ‘M’ for the *measured* position from the published radio maps in the RM paper, ‘V’ and ‘F’ for source position taken from the NVSS or FIRST survey databases, and ‘N’ for source position taken from NED; Col. (5) and (6): The Galactic longitude and latitude of a source; Col. (7) and (8): RM and uncertainty; Col. (9): Grade of measurements; Col. (10): Reference for RM observations; Col. (11): Telescope; Col. (12): Frequency range for RM observations; Col. (13): Number of frequencies or channels for observations; Col. (14): Angular resolution for RM determination; Col. (15): Object type; Col. (16): Redshift of the object; Col. (17): Reference of object redshift; Col. (18): Remarks or names in original references. This table is available in its entirety on the webpage <http://zmtt.bao.ac.cn/RM/>. A portion is shown here for guidance regarding its form and content.

To make the RM catalog available to the wider community, we have developed a web interface¹ that allows users to tabulate the RM data in a selected area and calculate the Galactic foreground RM.

2 COMPILING THE ROTATION MEASURE CATALOG

Faraday rotation is an effect that arises from propagation through the intervening magneto-ionized medium between the radiation source and us, as we discussed above, and ideally can be measured through multi-frequency polarization observations. However, the properties of polarized radio sources² and observational characteristics can make things complicated. For example, when a radio source has two or three components with different RMs (Law et al. 2011), observations with a low angular resolution that is not enough to resolve these components would produce a non-linear dependency between polarization angle and λ^2 (Xu & Han 2012; O’Sullivan et al. 2012), and hence observations at different frequencies with different resolutions would yield different RMs (Bernet et al. 2012). It is also possible that a source has different components (e.g. diffuse or compact), each having different spectral and/or polarization properties. Sources unresolved in low angular resolution observations often show extended and/or compact components with different RMs in high angular resolution observations (e.g. Reynolds et al. 2001). Polarization observations at different frequencies probe different depths of a source (Goldstein & Reed 1984). Therefore, properties of a source (number of components and the difference in their intrinsic polarization) as well as observational parameters (resolution, observational bands and the bandwidth) are important factors for determinations of RM.

Most extragalactic radio sources are compact cores in galaxy centers, jets or lobes from active galactic nuclei (AGNs). Observations with high angular resolutions and at high frequencies can always resolve jet regions because they can probe deeply into the emission cores; and the diffuse emission detected in lower resolution observations is often resolved and cannot be detected. There may be a large contribution to RM of the compact core from the medium between the core of the source and its edge, in addition to RMs from intergalactic space and the foreground Galactic RM. Observations with very high resolution and at high frequencies often help us to understand the intrinsic properties of radio sources (e.g. Algaba et al. 2012; O’Sullivan et al. 2011; Taylor & Zavala 2010; Taylor et al. 2005). On the other hand, observations with a low angular resolution at low frequencies suffer from differential Faraday rotation as well as internal and external Faraday dispersion (e.g. Sokoloff et al. 1998), and probe a much shallower ‘skin layer’ of the radio source. This has been found, for example, in M51 and other nearby galaxies (Fletcher et al. 2011; Heald et al. 2009; Braun et al. 2010; Bernet et al. 2012). The polarized emission from such a shallow layer more often gets the Faraday rotation in the intergalactic medium between the source and us.

Therefore, in this paper, we compile the RMs of point-like sources, unresolved by observations with resolution lower than $1''$ so that the RMs are mostly produced by the medium between the source of the emission and the observer, rather than dominated by intrinsic RMs from the sources. We do not collect the RMs of well-resolved sources with a resolution better than $1''$, for which the observed RMs are mostly intrinsic to the source. If an object has two components, and each component has a measured RM, we include them in our catalog as two sources. If a source component is resolved in polarization observations, we only include the average RM of the component in our catalog (e.g. Pedelty et al. 1989).

We compiled a catalog of RMs for 4553 sources, as shown in Table 1, which are ordered in terms of Right Ascension (J2000), by searching RMs that have been published in the literature after the 1980s. Earlier RM compilations by Simard-Normandin et al. (1981) and Broten et al. (1988) have

¹ <http://zmtt.bao.ac.cn/RM/>

² Here we define a *radio source* as a more or less independent radio emission component, while an *object* such as a quasar can produce a few radio sources, e.g. two unresolved lobes as two sources in addition to a compact core.

been included in our catalog directly. We may miss a small number of RMs by sporadic observations for individual objects, and will add new RMs to our catalog once they become available to us. In the following, we explain how we compiled our RM catalog in more detail.

Sources with multiple RM measurements: When two or more RMs are available for one source, we only choose one as the formal RM value of the source by considering uncertainties in the measurement and the number of observing frequencies, though in our catalog we list other RM values of the source for reference. We adopt a formal RM value in the following way.

First of all, we check the source positions. For the current density of polarized radio sources on the sky, we assume that any sources within $3''$ are the same source, because almost all sources in our catalog were observed with a resolution of $> 2''$ except for a few percent (since we set the $1''$ criterion above). Many old observations were made with a very low resolution of several arcminutes for very strong sources but no value for the resolution is given in literature, for which we mark them with “?” for the resolution in our catalog and check NED (NASA/IPAC Extragalactic Database), NVSS or other catalog for the position, see below. Second, for a given source, if the ionospheric RM was carefully corrected during observations, we take the RM as a formal value. We then check how many frequency bands or channels were used to derive the RM. The RM value derived from observations with more frequencies or channels is more reliable and in general good at removing the $n\pi$ ambiguity. We prefer to take the formal RM from observations with more channels or bands. Finally, we look at the uncertainty in RMs. The RM with a smaller uncertainty from a wider frequency range or more sensitive observations is preferably taken as the formal value. If two RM values are consistent with $2\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$, where σ_1 and σ_2 are the uncertainties of the two RM measurements, we take the one with the smaller uncertainty. If they differ by more than 2σ , we take the formal RM derived from the observations with more channels considering the similar emission region and Faraday depth for many channels in one band. If the same RM value and uncertainty for a source appears in two references, especially when the later authors cite the RM value obtained by the former authors, we give credit to the former authors.

In Table 1, we list the formal RM as one entry indicated by the number of the source, together with other RMs for this source indicated by “_1”, “_2” or “_n” in the numbering.

Coordinates: In Table 1 we use the following labels to indicate how we obtain source positions:

‘O’: We take the original published positions in the reference of RM observations;

‘M’: If coordinates were not published together with the RMs, we measured source positions from the images or figures in the papers where the RMs were published;

‘N’: In some papers, RMs are given for a list of sources with only object names without coordinates. We checked the NED (Helou et al. 1991, 1995) for positions. If observations for RMs have a high resolution, we assume that the source is associated with the core, and then take the object position that is given in NED. If the coordinates of the sources were misprinted in a paper, or if the uncertainties in the published coordinates were large, we also used the positions from NED.

‘V’: Some early RM observations have a low angular resolution, and RM data were listed by only specifying names of sources without coordinates. For these objects we first find the associated NED objects, then we take the coordinates from the NVSS (Condon et al. 1998).

‘F’: For some sources RMs have been derived for more than one component. If the coordinates of each of these components are not given in the references, we check and take the source positions from the VLA Faint Images of the Radio Sky survey (FIRST, Becker et al. 1995).

Uncertainty level and ionospheric correction: We rank the RM uncertainty into four levels: A for uncertainties smaller than $0-3 \text{ rad m}^{-2}$, B and C for $3-10 \text{ rad m}^{-2}$ and $10-30 \text{ rad m}^{-2}$, respectively, and D for uncertainties larger than 30 rad m^{-2} . In some publications (e.g. Stanghellini et al. 1998; Rossetti et al. 2008; Mantovani et al. 2009), the RM uncertainty was not given. For those cases we check the figures or position angle data, and sometimes calculate RM values and their uncertainties from polarization angle data given in a paper.

The RMs from the ionosphere in general have not been discussed in most previous papers, except for a few (Kim et al. 1994; Oren & Wolfe 1995; Minter & Spangler 1996; Brentjens 2008), for which we should thank the careful authors. The combination of the electron density and the magnetic field in the Earth's ionosphere causes different RMs for different directions on the sky, especially at sunrise or sunset (Sotomayor-Beltran et al. 2013). It may exceed $\pm 5 \text{ rad m}^{-2}$. If the contribution of ionospheric RM was not mentioned in a paper, we interpreted that the RMs in the paper have not been corrected for the ionospheric RM. Not correcting for the ionospheric RM may induce a systematic error for RM values, which in general should be $2 \sim 3 \text{ rad m}^{-2}$. If the ionospheric RM correction was explicitly made for RM measurements in the literature, we added “+” after the uncertainty level (i.e. “B+”).

Object type and redshift: We checked the names of objects (galaxies or quasars, etc.) for radio sources or source components. By cross-correlating source positions with $3''$, with NED and SIMBAD (the Set of Identifications, Measurements and Bibliography for Astronomical Data: Wenger et al. 2000), we found object types and redshifts. When NED and SIMBAD give different object types or redshifts for a given source, we use the information from NED.

The sky distribution of the compiled RMs is shown in Figure 1.

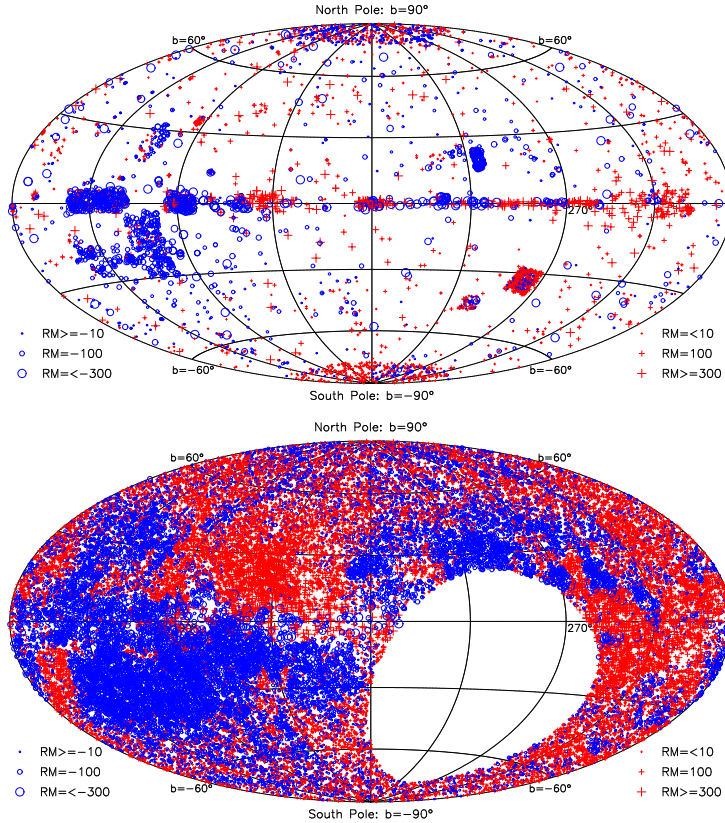


Fig. 1 The sky distribution of the compiled RMs in the Galactic coordinates (*upper*) and that of the NVSS RMs (*lower*). The linear sizes of the symbols are proportional to the square root of the RM values with limits of ± 10 and $\pm 300 \text{ rad m}^{-2}$. Red pluses indicate positive RMs, while blue circles indicate negative RMs.

3 UNCERTAINTY IN THE COMPILED RMS AND COMPARISON WITH THE NVSS RM CATALOG

Taylor et al. (2009) have reprocessed the NVSS polarization data of the two IF bands at 1435 MHz and 1365 MHz, and derived RM values for 37 543 sources from the two-band polarization data. The sky distribution of the NVSS RMs is also shown in Figure 1. Our compiled catalog contains RMs of 4553 sources derived from polarization observations at at least three frequencies. Over most of the sky, the RM distribution is sparse. The NVSS RM catalog obviously has the advantage of having a large number of sources and almost uniform sky coverage above a declination of -40° .

Here we compare the RM uncertainties in the RM catalog we compiled with the RM uncertainties from the RM catalog by Taylor et al. (2009). In Figure 2 we show the distributions of the RM uncertainties σ_{RM} for the compiled RM catalog and the NVSS RM catalog. The uncertainties of compiled RMs show a sharp peak at $\sigma_{\text{RM}} < 4 \text{ rad m}^{-2}$, because most of the compiled RM data are determined by polarization angles at more than three frequencies or channels and because the $\Delta\lambda^2$ range is large and there is no $n\pi$ ambiguity in the data. The uncertainties in the NVSS RMs show a broad distribution with a not-outstanding peak around $\sigma_{\text{RM}} \sim 13 \text{ rad m}^{-2}$, and a median uncertainty of $\sim 10.8 \text{ rad m}^{-2}$ (Schnitzeler 2010; Stil et al. 2011).

We also compared the RM values of 1024 sources that appear in both RM catalogs. In general, most RMs are consistent with each other within 20 rad m^{-2} (see Fig. 3), though the distribution of RM difference ΔRM extends to 50 rad m^{-2} , and a few sources even have differences up to 100 rad m^{-2} (see also fig. 3 of Pshirkov et al. 2011).

The systematic uncertainties in RM data should be but were rarely recognized in literature. The RMs compiled from the literature may have not been corrected for the ionospheric RM, which causes a systematic uncertainty, at most 3 rad m^{-2} . We selected the RMs of 36 sources in both RM catalogs which have formal uncertainties less than 1 rad m^{-2} , and checked their RM differences from the NVSS RMs. Because these sources are in general very bright and the RMs in the compiled RM catalog were well determined, the distribution of ΔRM must come from the systematic uncertainty of the NVSS RM catalog. We fit the distribution with a Gaussian and obtained a characteristic width

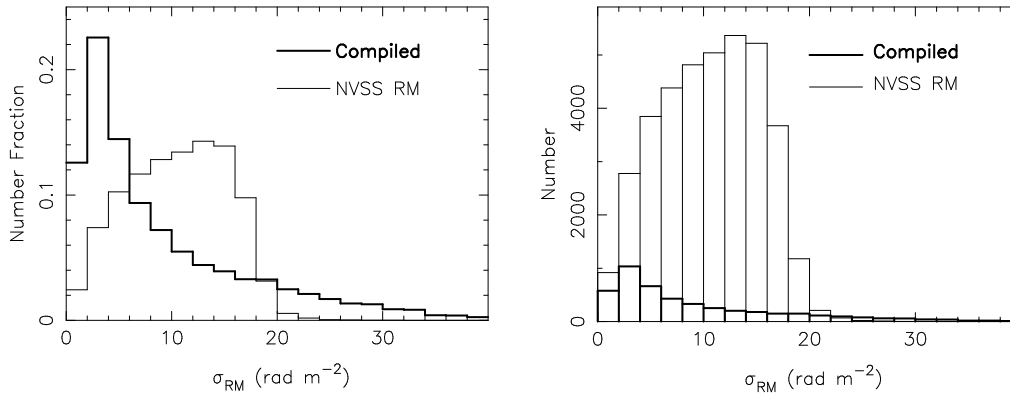


Fig. 2 Distribution of the uncertainty of RM measurements σ_{RM} for the compiled RM catalog and the NVSS RM catalog. The formal uncertainties of the compiled RMs have a peak at less than 4 rad m^{-2} , while the uncertainties of the NVSS RMs are widely distributed in the range $0 - 20 \text{ rad m}^{-2}$, with a peak around 13 rad m^{-2} . Note here that the systematic uncertainty of the two RM catalogs ($< 3 \text{ rad m}^{-2}$ for the compiled RMs and 10 rad m^{-2} for the NVSS RMs) have not been considered.

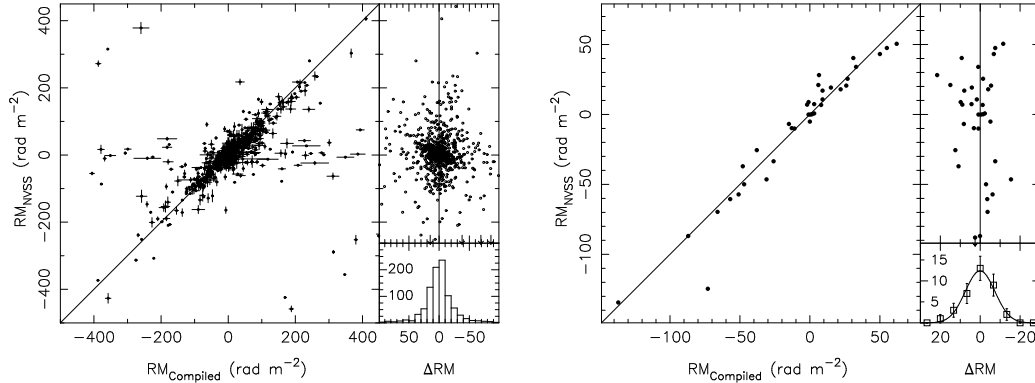


Fig. 3 Comparison of RM values for 1024 sources (*left*) in both the NVSS catalog and the catalog we compiled and for the 36 sources (*right*) in both catalogs with formal uncertainties less than 1 rad m^{-2} . Notice that the 36 sources are all bright sources and that their RMs have been well determined in the literature. The ΔRM values of these 36 sources follow a Gaussian distribution with a width of $10.46 \pm 1.45 \text{ rad m}^{-2}$, which mostly comes from the systematic uncertainty of the NVSS RM measurements.

of $\sigma_0 = 10.46 \pm 1.45 \text{ rad m}^{-2}$ (see the right panel of Fig. 3). Because the upper limit of the systematic uncertainty from our compiled RMs produced by the uncorrected ionospheric RM is 3 rad m^{-2} , and even if we discount such a maximal value of $\sigma_{\text{CM}}^{\text{sys}} = 3 \text{ rad m}^{-2}$, the systematic RM uncertainty of the NVSS RMs, in addition to the formal measurement uncertainty, should be $\sigma_{\text{NVSS}}^{\text{sys}} = \sqrt{\sigma_0^2 - (\sigma_{\text{CM}}^{\text{sys}})^2} = 10.0 \pm 1.5 \text{ rad m}^{-2}$. This systematic uncertainty can explain the randomly scattered distribution of a few tens of rad m^{-2} around the equivalent line in figure 7 of Mao et al. (2010), when the NVSS RMs are compared with the RMs derived by Mao et al. (2010) for radio sources close to the two Galactic poles. We therefore agree with Mao et al. (2010) that RMs derived in Taylor et al. (2009) can be used collectively to describe the large-scale Galactic RM sky by averaging over large areas, as we will do in the next section. However, one should be cautious to use the individual NVSS RM values even if they have a very small formal uncertainty, since these RMs can potentially be inaccurate due to the systematic uncertainty in RM that we identified. For example, two standard calibration sources, 3C286 (J133108.3 +303033, with expected RM = 0 rad m^{-2}) and 3C138 (J052109.9 +163822, with expected RM = -1 rad m^{-2}), have RM values of 8.8 ± 0.1 and $7.0 \pm 0.2 \text{ rad m}^{-2}$ in the NVSS RM catalog, respectively. These values are only understandable if such a systematic uncertainty of the NVSS RM catalog is taken into account.

4 THE GALACTIC FOREGROUND RM

We can derive the Galactic foreground RM from all available RM data. The observed RMs consist of the RM contributions from the polarized sources themselves, i.e. the intrinsic RM, the RM from intergalactic space and the RM from the interstellar medium in our Milky Way. The RM averaging process of a set of sources can smear out the random RM contributions from intergalactic space, which are not known exactly but could be random with an amplitude of a few rad m^{-2} according to simulations by Akahori & Ryu (2011) and recent studies by Xu & Han (2014). Because the common RM contribution of a set of neighboring radio sources comes from the interstellar medium in our Milky Way, the mean RM sky is therefore an excellent description of the Galactic foreground RM. In this averaging process, we should not use RMs that deviate significantly from neighboring RMs because those RMs are probably dominated by the RM contribution that is intrinsic to the source.

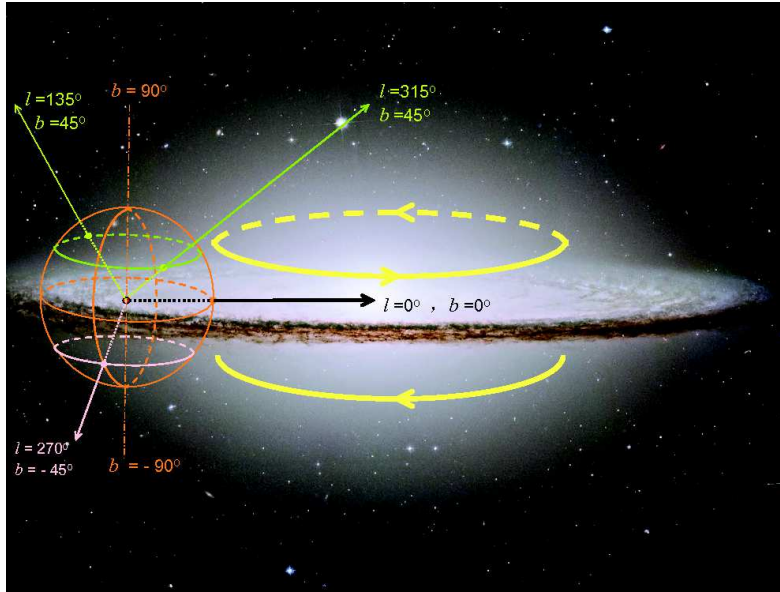


Fig. 4 The Galactic coordinates and azimuthal magnetic fields in the Galactic halo with reversed directions above and below the Galactic plane. Such halo magnetic fields can explain the antisymmetric RM sky in the inner Galaxy shown in Fig. 1 as proposed originally by Han et al. (1997).

Many authors have investigated structures in the RM sky, e.g. Simard-Normandin & Kronberg (1980); Han et al. (1997, 1999); Taylor et al. (2009); Stil et al. (2011); Oppermann et al. (2012). As shown in Figure 1, the RM distribution shows large-scale coherent structures on scales of up to tens of degrees. The most striking feature is the antisymmetric (quadrupole-like) RM structure in the inner Galaxy with respect to the Galactic plane and the Galactic meridian at $l \sim 0^\circ$, as discussed by Han et al. (1997, 1999), which consists of positive RMs in the upper left and lower right quadrants and negative RMs in the upper right and lower left quadrants. Such a pattern has been attributed to large-scale toroidal magnetic fields in the Galactic halo that go in opposite directions above and below the Galactic plane (see Fig. 4), originally pointed out by Han et al. (1997, 1999) and later modeled by Prouza & Šmída (2003); Sun et al. (2008); Pshirkov et al. (2011); Jansson & Farrar (2012); Ferrière & Terral (2014). In the two Galactic pole regions, RMs have much smaller values than those near the Galactic plane, as the magnetic fields in our Milky way are dominated by the azimuthal components parallel to the Galactic plane (Han et al. 1999; Mao et al. 2010). Small scale structures in the RM sky are related to known foreground objects, such as HII regions (Harvey-Smith et al. 2011; Rodríguez et al. 2012), SNRs (Kim 1988; Simonetti 1992; Sun et al. 2011) and high velocity clouds (McClure-Griffiths et al. 2010) in our Milky Way. Here, we do not study the small-scale RM structure in detail. Instead we derive the Galactic foreground RM by using the RM catalog we compiled together with the NVSS RM catalog. We first derive the Galactic foreground RM, and then compare our result with that obtained by Oppermann et al. (2012).

4.1 The Galactic Foreground RM and its Uncertainty

We take all available RM measurements from the compiled RM catalog and the NVSS RM catalog to estimate the Galactic RM foreground and its uncertainty. If multiple RMs are listed for a single source, we only took the formal best value. In total, we have RMs for 41 072 sources. Then, any RMs with a formal uncertainty larger than 30 rad m^{-2} are discarded, because they are not reliable. This leaves us 40 894 sources.

In principle, because of randomness of intergalactic RM contributions and intrinsic RMs of radio sources, the mean RM of many radio sources in a small patch of the sky represents the Galactic foreground RM. Because of our position in the Milky Way as shown in Figure 4 and because of the different properties of the regular and random magnetic field in the disk and the halo, the correlation scale of the RM distribution should be very different in different parts of the sky. The RM distributions are related to each other on large angular scales for different parts of the halo in the inner Galaxy, but the RM values of background sources vary on small angular scales in the disk directions because of density fluctuations of the interstellar medium and reversed fields in the spiral arms.

Previously, there were efforts to estimate the Galactic foreground RM. Frick et al. (2001) proposed an RM estimation method which works on a sphere using wavelet approaches; Dineen & Coles (2005) performed spherical harmonic analysis of RM data; Short et al. (2007) put forward Gaussian process convolution models based on the Markov Chain Monte Carlo method to estimate the Galactic RM foreground. Oppermann et al. (2012) proposed to use the signal reconstruction algorithm for RM sky estimation. When RM data for the entire sky are analyzed using spherical harmonics (Dineen & Coles 2005) or rely on spatial correlations (Oppermann et al. 2012; Johnston-Hollitt et al. 2004), RMs from different parts of the sky are assumed to be correlated in a similar format. We believe that the most secure approach for deriving the Galactic foreground RM is to calculate the mean RM from a set of RM measurements of sources in a small patch of sky.

Here we use a simple statistical approach, the weighted average method, to derive the Galactic foreground RM. Every measurement in a local sky area around a given line of sight is evaluated and weighted to calculate the mean, $\langle \text{RM} \rangle$, and the uncertainty of the mean, $\sigma_{\langle \text{RM} \rangle}$:

$$\begin{cases} \langle \text{RM} \rangle = \frac{\sum_{i=1}^N (w_i \text{RM}_i)}{\sum_{i=1}^N w_i}, \\ \sigma_{\langle \text{RM} \rangle} = \left(\frac{\sum_{i=1}^N w_i (\text{RM}_i - \langle \text{RM} \rangle)^2}{(N-1) \sum_{i=1}^N w_i} \right)^{1/2}. \end{cases} \quad (4)$$

The weight factor w_i is defined as

$$w_i = w_{\sigma_{\text{RM}}} \cdot w_{\text{iono}} \cdot w_{\text{offset}}, \quad (5)$$

where $w_{\sigma_{\text{RM}}}$ is the weight for measurement uncertainty, which consists of not only the formal observational uncertainty $\sigma_{\text{RM}}^{\text{obs}}$ but also the systematic uncertainty $\sigma_{\text{RM}}^{\text{sys}}$ as we discussed above, i.e.

$$\sigma_{\text{RM}} = \left[(\sigma_{\text{RM}}^{\text{obs}})^2 + (\sigma_{\text{RM}}^{\text{sys}})^2 \right]^{1/2}.$$

We adopt the $\sigma_{\text{RM}}^{\text{sys}} = 0 \text{ rad m}^{-2}$ for the compiled RMs, and $\sigma_{\text{RM}}^{\text{sys}} = 10 \text{ rad m}^{-2}$ for the NVSS RMs. RM data of sources nearer to the sightline with better quality play a larger role in determining the Galactic RM foreground at this direction. After comparisons, we found that in practice $w_{\sigma_{\text{RM}}} =$

$1/\sigma_{\text{RM}}^{1/2}$ is superior to $w_{\sigma_{\text{RM}}} = 1/\sigma_{\text{RM}}$ or $w_{\sigma_{\text{RM}}} = 1/\sigma_{\text{RM}}^2$ for deriving the Galactic foreground RM, because otherwise RM measurements with slightly better precision are overemphasized in the weighted average. The second term is the weight for the ionospheric RM correction³. If the RM of a source has been corrected for the ionospheric RM, then we set $w_{\text{iono}} = 1.0$, otherwise $w_{\text{iono}} = 0.5$. The final term is the weight factor w_{offset} for the angular distance a of a source to the given line of sight, which is defined as the Gaussian function $w_{\text{offset}} = \exp(-a^2/2a_0^2)$, where a_0 is the characteristic width. RM values of farther sources with a larger a have less weight in calculations of the Galactic foreground RM for a given direction. For example, $a = 0$, $w_{\text{offset}} = 1$; $a = a_0$, $w_{\text{offset}} = 0.607$; and $a = 2a_0$, $w_{\text{offset}} = 0.135$. Oren & Wolfe (1995) calculated the mean RM for all sightlines within 20° , assigning equal weights to each of these measurements. Similarly, Han et al. (1997) used a radius of 15° . With the larger surface density of sightlines in our sample, we can choose a much smaller $a_0 = 3^\circ$. We calculate the mean RM using RM data within $2a_0$ for any given direction. Over most of the NVSS region there are at least 10 measurements within this region. In the southern sky of $\text{Dec} < -40^\circ$, however, the RMs are scarce, and we have to increase a_0 from 3° to 6° or 9° or 12° so that we always use at least 10 RMs to calculate the average RM. In the future, when RM data of more radio sources will become available, one can choose a smaller a_0 . We make it possible to change the weighting scheme used to calculate the Galactic foreground RM on our website.

To derive the Galactic foreground RM map, as the first step it is necessary to filter out the “anomalous” RMs if they are obviously deviating from their neighbors, because such RMs are almost certainly dominated by intrinsic RMs. Such a filtering procedure for outliers was not done by Oppermann et al. (2012), but has already been included in some early work (Han et al. 1997, 1999) and recent modeling (e.g. Jansson & Farrar 2012). We compare the RM value of each source with the weighted mean in Equation (4) and the weighted standard deviation

$$\sigma = \left[\sum_{i=1}^N w_i \left(\text{RM}_i - \langle \text{RM} \rangle \right)^2 / \left(\sum_{i=1}^N w_i \right) \right]^{1/2}$$

of neighboring sources within 3° , 6° , 9° or 12° as mentioned above, except for the target source. If the RM of the target source deviates more than 3σ from the mean of surrounding sources, then we discard it as an outlier. Galaxy clusters can contribute large RMs to background sources (Clarke et al. 2001; Bonafede et al. 2010), RMs of some radio sources behind galaxy clusters are “anomalous,” and hence can be removed by this step in our analysis. After iterating a few times, we get good RMs for 39 984 sources that we can use in our reconstruction of the Galactic foreground RM (see Fig. 5). The scarcity of RM data is obvious in the region $\text{Dec} < -40^\circ$ which is not covered by the NVSS.

Using these RM data with the outliers removed, and by applying the weighted average in Equation (4), we obtain the RM map of the Galactic foreground and its uncertainty, which we show in Figure 6. Small-scale structures appear near the Galactic plane and towards some HII regions (e.g. Sh 2-27 at $(l = 8.0, b = +23.5)$, Harvey-Smith et al. 2011), and the large-scale foreground RM is also visible away from the Galactic plane. The uncertainty is obviously large in the southern sky at $\text{Dec} < -40^\circ$ due to the shortage of RM data. A larger scatter in the RM data and hence a larger

³ Most previous authors believe that the ionospheric RM has a small value, within $\pm 5 \text{ rad m}^{-2}$, and hence it is not worth mentioning or correcting in RM measurements. However, it is very important to make the ionospheric RM correction for many fields of research on the intergalactic medium, and it will become even more important during the SKA era in the future. For example, when one looks for the residual RM evolution of a few rad m^{-2} with redshift from intergalactic magnetic fields or fields in the cosmic web (e.g. Xu & Han 2014), only RM observations with proper ionospheric RM corrections can really reduce such a systematic uncertainty in the estimation of the Galactic foreground RMs and ultimately the residual RMs. Therefore, RMs with proper ionospheric RM corrections are emphasized here, and are given a double weight in Sect. 4.1 for the averaging method so that it plays a “calibration” role. However, because of the relatively small number of RMs with ionospheric RM correction, no obvious difference can be seen in the final foreground RM map if one takes $w_{\text{iono}} = 1.0$ for all RM data.

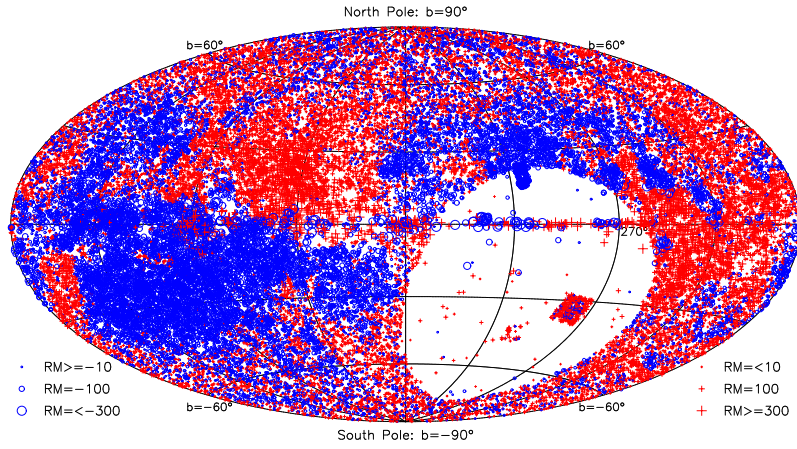


Fig. 5 The RM distribution for sources from the compiled RM catalog and the NVSS RM catalog. Outliers and RMs with an uncertainty larger than 30 rad m^{-2} have been discarded.

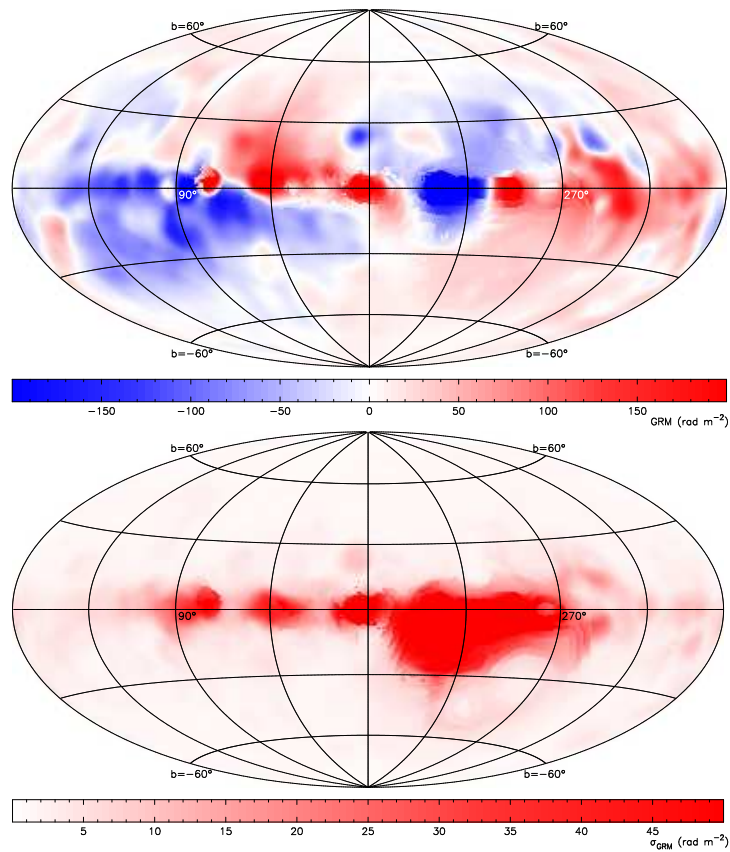


Fig. 6 The Galactic foreground RM map (*top panel*) and its associated uncertainty map (*bottom panel*) that we calculated by combining the compiled RM catalog with the RM catalog by Taylor et al. (2009).

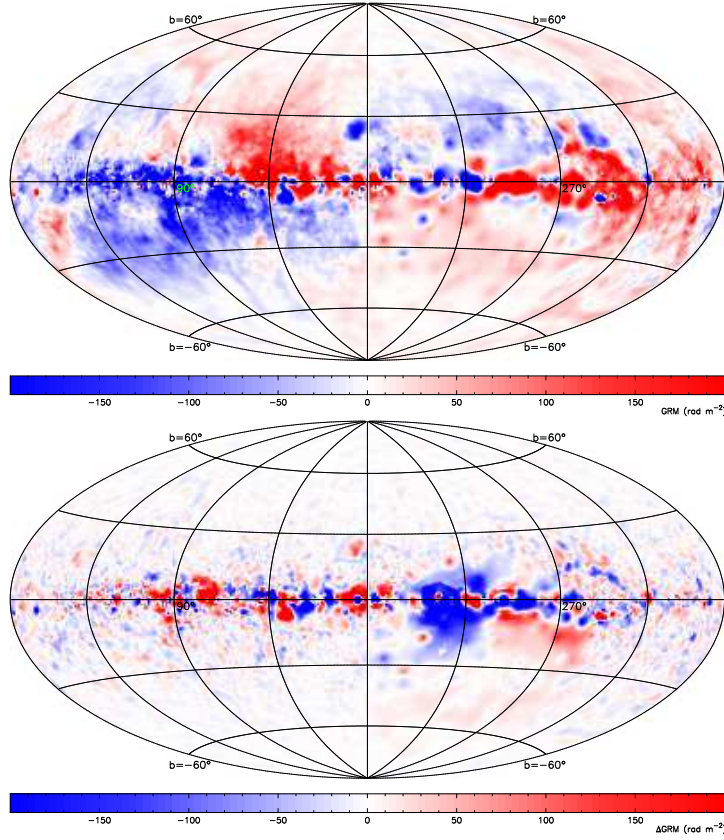


Fig. 7 The Galactic foreground RM derived by Oppermann et al. (2012) using information field theory, and the difference map from our RM foreground.

uncertainty in the estimated Galactic foreground RM is found near the Galactic plane, especially in the inner Galaxy near tangential directions of spiral arms, where more turbulent clouds along the line of sight are expected.

4.2 Comparison of Our Foreground RM Map with that of Oppermann et al. (2012)

At present we have calculated the weighted average RM of the cleaned RM data for the Galactic foreground RM. Given enough data points in a small area for averaging, our approach is very simple and very straightforward, in comparison with previous efforts (Frick et al. 2001; Dineen & Coles 2005; Short et al. 2007; Oppermann et al. 2012). The latest such an attempt before our work was made by Oppermann et al. (2011, 2012) who used a signal reconstruction algorithm based on information field theory (Enßlin et al. 2009). They took into account the spatial correlations and used the formalism of an *extended critical filter* (Oppermann et al. 2011) to reconstruct the map for the Galactic foreground RM (see Fig. 7). Using priors for the signal s , noise n , the angular power spectrum and the noise correction factors, they calculate the mean $m = \langle s \rangle_{P(s|d)}$ from data d , i.e. the reconstructed signal by iterating filtering equations (eq. (9) – (11) in Oppermann et al. 2012). The posterior mean for the Galactic Faraday depth is given by $\langle \phi \rangle = pm$. The critical step in the filtering process is

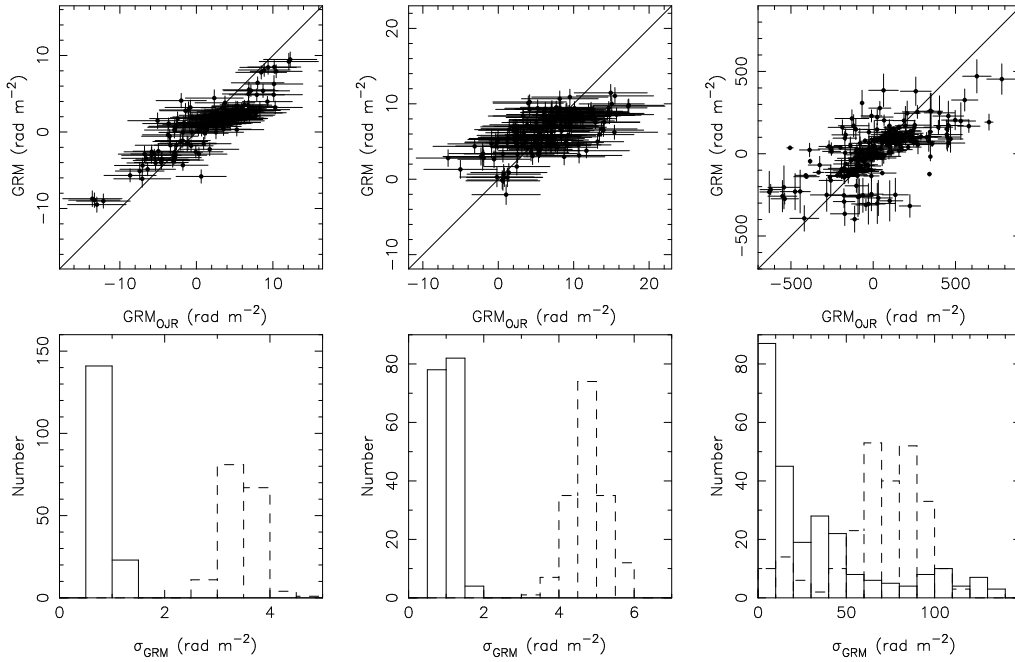


Fig. 8 Comparison of the Galactic foreground RM calculated by our weighted mean and by Oppermann et al. (2012) in the upper panels for three regions near the North Galactic pole ($b > 75^\circ$, *left panels*), the South Galactic pole ($b < -75^\circ$, *middle panels*) and the Galactic plane of all Galactic longitudes ($b = 0^\circ$, *right panels*). We calculate the Galactic foreground RM for 160 of 3279 pixels in each polar cap with a separation of pixels larger than 1° , and 256 equally separated pixels along the Galactic plane. The distributions of uncertainty of the Galactic foreground RM are compared in the lower panels, with a solid line for our calculations and a dashed line for the results by Oppermann et al. (2012).

to identify the posterior probability density based on prior information. The relation between the posterior mean and measured data contains an information propagator D (Enßlin et al. 2009) which describes how the information contained in the data at one position propagates to another position. The filtering equations are designed in the framework of a series expansion in spherical harmonics, where the minimum length scale l_{\max} is limited by the pixel size of the discretization. In their final Faraday depth map (see the upper panel of Fig. 7), there are many small structures. RMs in some areas that differ greatly from their surroundings come from outliers or RM values with very large uncertainties (see the difference map in the lower panel of Fig. 7). The angular resolution of their “extended critical filter” algorithm seems to be high enough to partially pick up anomalous RM values, though such a resolution seems to be necessary for recovering small-scale structures near the Galactic plane if there are enough RM data. On the other hand, their approach seems to be very good at extrapolating the foreground RM in the undersampled halo region at $\text{Dec} < -40^\circ$ using spherical harmonic components. In our approach we only consider RM data close to any given line of sight, without RM outliers, for the Galactic foreground RM. The RMs with different uncertainties are simply weighted for the averaging calculations. The uncertainty in the map of the Galactic foreground RM that we constructed depends on the number and quality of RM data points in a local area.

We compare the values of the Galactic foreground RM calculated by our method and by Oppermann et al. (2012) towards the North Galactic Pole, the South Galactic Pole and the Galactic

plane (see Fig. 8), and find that they are more or less consistent. However, in general our approach gives more reliable estimates of the Galactic RM foreground with smaller uncertainties by using more than 30 sources for averaging. The uncertainty for pixels near the Galactic plane is dominated by scatter in the RM data.

5 CONCLUDING REMARKS

We compiled an RM catalog of 4553 sources which have a small systematic uncertainty. Even though the NVSS RM catalog by Taylor et al. (2009) contains 37 543 RMs, the measurement uncertainties of their RMs are large and the RM values suffer from an additional systematic uncertainty of 10.0 ± 1.5 rad m⁻². The RM catalog we compiled provides a database for future calibration or comparisons with wideband observations.

We make all compiled RM data publicly available on this webpage: <http://zmtt.bao.ac.cn/RM/>, and provide an interface on this webpage to extract the RM data for a region and to calculate the Galactic RM foreground. The RM data can be downloaded from the webpage. We will continuously update the RM catalog on our webpage by including newly published RM values. Knowing the RM of the Galactic foreground is important for many research fields, such as magnetic fields in galaxy clusters (e.g. Bonafede et al. 2013), Galactic bubbles (e.g. Savage et al. 2013), HII regions (e.g. Harvey-Smith et al. 2011) and SNRs (e.g. Sun et al. 2011). Using the RM catalog that we compiled together with the NVSS RM catalog, users can always get the best estimates of the Galactic foreground RM for any direction in the sky by using a weighted averaging method.

Finally, we would like to remind the users of the compiled RM catalog to also cite the original RM observation papers if any individual RM data are used.

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References

- Akahori, T., & Ryu, D. 2011, *ApJ*, 738, 134
- Algaba, J. C., Gabuzda, D. C., & Smith, P. S. 2012, *MNRAS*, 420, 542
- Athreya, R. M., Kapahi, V. K., McCarthy, P. J., & van Breugel, W. 1998, *A&A*, 329, 809
- Becker, R. H., White, R. L., & Helfand, D. J. 1995, *ApJ*, 450, 559
- Bernet, M. L., Miniati, F., & Lilly, S. J. 2012, *ApJ*, 761, 144
- Bonafede, A., Feretti, L., Murgia, M., et al. 2010, *A&A*, 513, A30
- Bonafede, A., Vazza, F., Brüggen, M., et al. 2013, *MNRAS*, 433, 3208
- Braun, R., Heald, G., & Beck, R. 2010, *A&A*, 514, A42
- Brentjens, M. A. 2008, *A&A*, 489, 69
- Brentjens, M. A., & de Bruyn, A. G. 2005, *A&A*, 441, 1217
- Broderick, J. W., Bryant, J. J., Hunstead, R. W., Sadler, E. M., & Murphy, T. 2007, *MNRAS*, 381, 341

- Broten, N. W., MacLeod, J. M., & Vallee, J. P. 1988, *Ap&SS*, 141, 303
 Brown, J. C., Haverkorn, M., Gaensler, B. M., et al. 2007, *ApJ*, 663, 258
 Brown, J. C., Taylor, A. R., & Jackel, B. J. 2003, *ApJS*, 145, 213
 Clarke, T. E., Kronberg, P. P., & Böhringer, H. 2001, *ApJ*, 547, L111
 Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, *AJ*, 115, 1693
 Dineen, P., & Coles, P. 2005, *MNRAS*, 362, 403
 Eichendorf, W., & Reinhardt, M. 1979, *Ap&SS*, 61, 153
 Enßlin, T. A., Frommert, M., & Kitauro, F. S. 2009, *Phys. Rev. D*, 80, 105005
 Ferrière, K., & Terral, P. 2014, *A&A*, 561, A100
 Fletcher, A., Beck, R., Shukurov, A., Berkhuijsen, E. M., & Horellou, C. 2011, *MNRAS*, 412, 2396
 Frick, P., Stepanov, R., Shukurov, A., & Sokoloff, D. 2001, *MNRAS*, 325, 649
 Gaensler, B. M., Haverkorn, M., Staveley-Smith, L., et al. 2005, *Science*, 307, 1610
 Gießbübel, R., Heald, G., Beck, R., & Arshakian, T. G. 2013, *A&A*, 559, A27
 Goldstein, S. J., Jr., & Reed, J. A. 1984, *ApJ*, 283, 540
 Govoni, F., Dolag, K., Murgia, M., et al. 2010, *A&A*, 522, A105
 Hammond, A. M., Robishaw, T., & Gaensler, B. M. 2012, *arXiv:1209.1438*
 Han, J. L., Beck, R., & Berkhuijsen, E. M. 1998, *A&A*, 335, 1117
 Han, J. L., Manchester, R. N., Berkhuijsen, E. M., & Beck, R. 1997, *A&A*, 322, 98
 Han, J. L., Manchester, R. N., & Qiao, G. J. 1999, *MNRAS*, 306, 371
 Harvey-Smith, L., Madsen, G. J., & Gaensler, B. M. 2011, *ApJ*, 736, 83
 Heald, G., Braun, R., & Edmonds, R. 2009, *A&A*, 503, 409
 Helou, G., Madore, B. F., Schmitz, M., et al. 1991, in *Databases and On-line Data in Astronomy, Astrophysics and Space Science Library*, vol. 171, eds. M. A. Albrecht & D. Egret, 89
 Helou, G., Madore, B. F., Schmitz, M., et al. 1995, in *Information & On-Line Data in Astronomy, Astrophysics and Space Science Library*, vol. 203, eds. D. Egret & M. A. Albrecht, 95
 Hennessy, G. S., Owen, F. N., & Eilek, J. A. 1989, *ApJ*, 347, 144
 Jansson, R., & Farrar, G. R. 2012, *ApJ*, 761, L11
 Johnston-Hollitt, M., & Ekers, R. D. 2004, *arXiv: astro-ph/0411045*
 Johnston-Hollitt, M., Hollitt, C. P., & Ekers, R. D. 2004, in *The Magnetized Interstellar Medium*, eds. B. Uyaniker, W. Reich, & R. Wielebinski, 13
 Kim, K.-T. 1988, *Journal of Korean Astronomical Society*, 21, 133
 Kim, K.-T., Kronberg, P. P., Dewdney, P. E., & Landecker, T. L. 1994, *A&AS*, 105, 385
 Law, C. J., Gaensler, B. M., Bower, G. C., et al. 2011, *ApJ*, 728, 57
 Leahy, J. P. 1987, *MNRAS*, 226, 433
 Mantovani, F., Mack, K.-H., Montenegro-Montes, F. M., Rossetti, A., & Kraus, A. 2009, *A&A*, 502, 61
 Mao, S. A., Gaensler, B. M., Haverkorn, M., et al. 2010, *ApJ*, 714, 1170
 Mao, S. A., Gaensler, B. M., Stanimirović, S., et al. 2008, *ApJ*, 688, 1029
 Mao, S. A., McClure-Griffiths, N. M., Gaensler, B. M., et al. 2012, *ApJ*, 759, 25
 McClure-Griffiths, N. M., Madsen, G. J., Gaensler, B. M., McConnell, D., & Schnitzeler, D. H. F. M. 2010, *ApJ*, 725, 275
 Minter, A. H., & Spangler, S. R. 1996, *ApJ*, 458, 194
 Oppermann, N., Junklewitz, H., Robbers, G., et al. 2012, *A&A*, 542, A93
 Oppermann, N., Robbers, G., & Enßlin, T. A. 2011, *Phys. Rev. E*, 84, 041118
 Oren, A. L., & Wolfe, A. M. 1995, *ApJ*, 445, 624
 O'Sullivan, S. P., Brown, S., Robishaw, T., et al. 2012, *MNRAS*, 421, 3300
 O'Sullivan, S. P., Gabuzda, D. C., & Gurvits, L. I. 2011, *MNRAS*, 415, 3049
 Pedelty, J. A., Rudnick, L., McCarthy, P. J., & Spinrad, H. 1989, *AJ*, 97, 647
 Prouza, M., & Šmída, R. 2003, *A&A*, 410, 1

- Pshirkov, M. S., Tinyakov, P. G., Kronberg, P. P., & Newton-McGee, K. J. 2011, *ApJ*, 738, 192
- Reynolds, C., Cawthorne, T. V., & Gabuzda, D. C. 2001, *MNRAS*, 327, 1071
- Rodríguez, L. F., Gómez, Y., & Tafoya, D. 2012, *MNRAS*, 420, 279
- Rossetti, A., Dallacasa, D., Fanti, C., Fanti, R., & Mack, K.-H. 2008, *A&A*, 487, 865
- Savage, A. H., Spangler, S. R., & Fischer, P. D. 2013, *ApJ*, 765, 42
- Schnitzeler, D. H. F. M. 2010, *MNRAS*, 409, L99
- Short, M. B., Higdon, D. M., & Kronberg, P. P. 2007, *Bayesian Analysis*, 2, 665
- Simard-Normandin, M., & Kronberg, P. P. 1980, *ApJ*, 242, 74
- Simard-Normandin, M., Kronberg, P. P., & Button, S. 1981, *ApJS*, 45, 97
- Simonetti, J. M. 1992, *ApJ*, 386, 170
- Sofue, Y., & Fujimoto, M. 1983, *ApJ*, 265, 722
- Sokoloff, D. D., Bykov, A. A., Shukurov, A., et al. 1998, *MNRAS*, 299, 189
- Sotomayor-Beltran, C., Sobey, C., Hessels, J. W. T., et al. 2013, *A&A*, 552, A58
- Stanghellini, C., O’Dea, C. P., Dallacasa, D., et al. 1998, *A&AS*, 131, 303
- Stil, J. M., Taylor, A. R., & Sunstrum, C. 2011, *ApJ*, 726, 4
- Sun, X. H., Reich, W., Waelkens, A., & Enßlin, T. A. 2008, *A&A*, 477, 573
- Sun, X. H., Reich, W., Wang, C., Han, J. L., & Reich, P. 2011, *A&A*, 535, A64
- Tabara, H., & Inoue, M. 1980, *A&AS*, 39, 379
- Taylor, A. R., Stil, J. M., & Sunstrum, C. 2009, *ApJ*, 702, 1230
- Taylor, G. B., Fassnacht, C. D., Sjouwerman, L. O., et al. 2005, *ApJS*, 159, 27
- Taylor, G. B., & Zavala, R. 2010, *ApJ*, 722, L183
- Van Eck, C. L., Brown, J. C., Stil, J. M., et al. 2011, *ApJ*, 728, 97
- Wenger, M., Ochsenbein, F., Egret, D., et al. 2000, *A&AS*, 143, 9
- Xu, J., & Han, J. L. 2012, *Chinese Astron. Astrophys.*, 36, 107
- Xu, J., & Han, J. L. 2014, *MNRAS*, 442, 3329